γ

p. 6

WALKING ROBOT: A DESIGN PROJECT FOR UNDERGRADUATE STUDENTS

UNIVERSITY OF MARYLAND
DEPARTMENT OF MECHANICAL ENGINEERING

N91-18140

The design and construction of the University of Maryland walking machine was completed during the 1989-1990 academic year. It was required that the machine be capable of completing a number of tasks including walking in a straight line, turning to change direction, and maneuvering over an obstacle such as a set of stairs. The machine consists of two sets of four telescoping legs that alternately support the entire structure. A gear-box and crank-arm assembly is connected to the leg sets to provide the power required for the translational motion of the machine. By retracting all eight legs, the robot comes to rest on a central "Bigfoot" support. Turning is accomplished by rotating the machine about this support. The machine can be controlled by using either a user-operated remote tether or the onboard computer for the execution of control commands. Absolute encoders are attached to all motors (leg, main drive, and Bigfoot) to provide the control computer with information regarding the status of the motors (up-down motion, forward or reverse rotation). Long- and short-range infrared sensors provide the computer with feedback information regarding the machine's position relative to a series of stripes and reflectors. These infrared sensors simulate how the robot might sense and gain information about the environment of Mars.

INTRODUCTION

The University of Maryland walking machine, Prototerp IV, was designed to be a martian planetary rover. Among the design requirements were that the machine be able to support itself on a set of movable legs and not depend on rollers or wheels for its maneuverability. In addition, it was required that the machine be able to "walk" in a straight line and turn to change the direction of motion. These requirements allow the machine to follow any path as well as walk over an irregular surface. The University of Maryland Planetary Rover has the capability to obtain control feedback information regarding its immediate environment and thus can autonomously compute any desired and obtainable path.

The machine was designed and built by the senior Mechanical and Electrical Engineering students of ENME 408 over the two-semester period of the 1989-1990 academic year. The motivation behind building Prototerp IV was to provide the students with practical experience to improve and refine their engineering skills by combining their talents as they worked toward a common goal. In addition, this project aimed to provide an environment where the students learn about robotic systems and apply their creativity to construction of their walking machine.

Prototerp IV required two semesters to evolve. The machine was designed in the fall of 1989, and construction was completed in the spring of 1990. For both semesters, the students were divided into groups that were to address a particular aspect of the project.

In the first semester, the students proposed the initial design. There were four groups: (1) the chassis group, which was responsible for the chassis, drive-line, and the Bigfoot; (2) the leg group, which was responsible for the designing of the legs; (3) the control group, which was responsible for the control hardware and software as well as the selection of all motors; and (4) the sensors group, which was responsible for the selection of rotation, position, and vision sensors.

In the second semester, the students were responsible for the actual construction of the walking machine. As in the first semester, the students were split into groups that were responsible for reviewing the design proposal of the previous semester and suggesting changes to improve the overall design of the machine. There were five groups involved during the second semester: (1) the chassis and Bigfoot group; (2) the leg group; (3) the drive-line group; (4) the control hardware group; and (5) the control software group.

CHASSIS AND BIGFOOT

The chassis of Prototerp IV provides a rigid support to which all other components are attached. Primary considerations for the chassis design include durability, functionality, weight, balance, and safety.

Many materials were considered for the design of the chassis. Preliminary calculations indicated that the robot would weigh approximately 150 lb. In order to prevent bending or flexing along the length or width of the chassis, it was determined that a 2″ × 3″ 1024 aluminum box channel would be best suited to fulfill the requirements[1]. The advantages of using aluminum include its high strength-to-weight ratio and the ease with which it can be machined to proper dimensions.

The overall shape of the body resembles a composite I-beam. To allow for the placement of the gearbox, crank assemblies, computer, and power-packs, the web of the composite I-beam is made of two sections of box channel separated by a distance of 11″. Mounted on the outer edge of each web section, near the center, are two leg assembly slider rod support brackets (Fig. 1). Initially, these support brackets were to be a single piece of aluminum channel that bisected the web at the midpoint. This effectively cut the chassis into two pieces. It

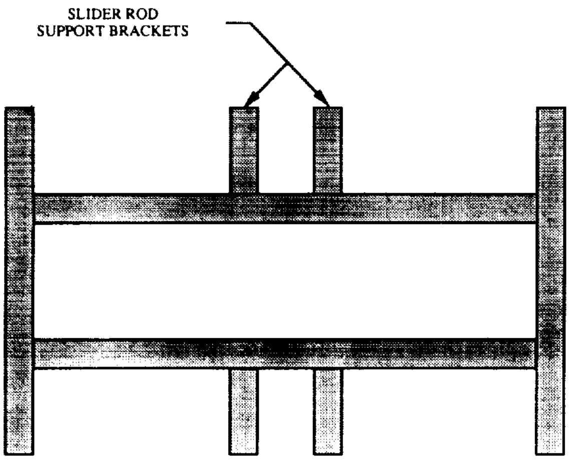


Fig. 1. Chassis

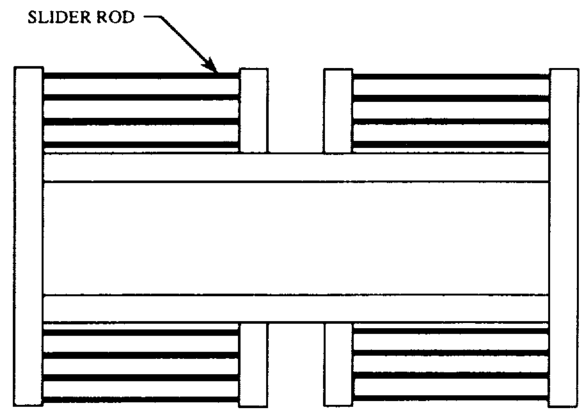


Fig. 2. Slider Rods

was then determined that this design would significantly reduce the rigidity of the robot, which could result in buckling and failure. Upon review, it was decided that the best approach was to make web sections continuous, and mount the slider rod support brackets and slider rods directly to them.

It is important that the chassis remains properly aligned with 90° angles at each corner. Further, a crucial requirement for the leg assembly slider rods is that they should be parallel to one another to reduce drag during each stride (Fig. 2). To ensure that these conditions are met, connections between the sections of the chassis must remain rigid. Therefore, a $3'' \times 3''$ aluminum angle was used as a brace at the inside of each section with four bolts at each leg of the brace. The junctions were tested with a design factor of safety of 5 to ensure that the supports would hold under the repetitive torsional and bending loads.

There are many components that will ride on the chassis including the onboard computer, main-drive gearbox, Bigfoot motor, eight leg motors, photo-interrupter, encoders, infrared sensors, and battery packs. The gearbox is the heaviest component and is located as close as possible to the center of gravity. The remainder of the free-floating parts are positioned carefully to distribute the weight as evenly as possible throughout the chassis and to locate the center of gravity of the robot close to the ground for stability. For safety in the design, all components are securely fastened to the chassis and all sharp edges are rounded off. The powerful crank arms and gearbox are covered with a plastic shell to prevent them from catching anything as they move the connecting rods.

The design of Prototerp IV incorporates the use of a centrally located "Bigfoot" on which the robot pivots when executing a turn. Because of this design feature, the body is required to be symmetric about the centroidal axes to ensure balance and reduce friction. This Bigfoot consists of a fixed shaft on which a geared collar rotates. The "legs" of the Bigfoot are two 1/2"-square, 2"-long pieces of aluminum channel that are connected directly to the bottom of the collar. At the ends of each channel are threaded posts that act as "feet." They have rubber caps attached at the ends to provide a nonslip contact with the floor as the robot is turning. The Bigfoot motor shaft is geared directly to the Bigfoot assembly by a collar. The Bigfoot is capable of turning the robot 90° in 5 sec.

DRIVE-LINE

It is the function of the drive-line to provide the forward locomotive force for Prototerp IV. Several different designs were considered throughout the evolution of the machine. The final design consists of a gearbox and crank-arm assembly that transmit force from a single motor to the leg groups.

The prime mover of the drive-line is the gearbox assembly. The driving force of the gearbox is provided by a 1/20-hp electric motor. This motor operates on 12 V DC, and has a built-in 36.7:1 gear reduction transmission. Attached to the output shaft of the motor is a 3", 72-tooth spur gear that meshes in line with two identical spur gears. The second and third gears were each connected by a shaft and key to a chain sprocket (Fig. 3).

A length of chain was used to transmit the motive force from the gearbox to the 5.41"-long crank arms through the use of sprockets. Using this configuration, it was possible to create

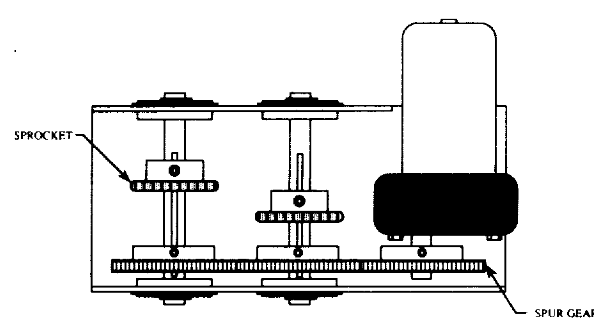


Fig. 3. Gearbox

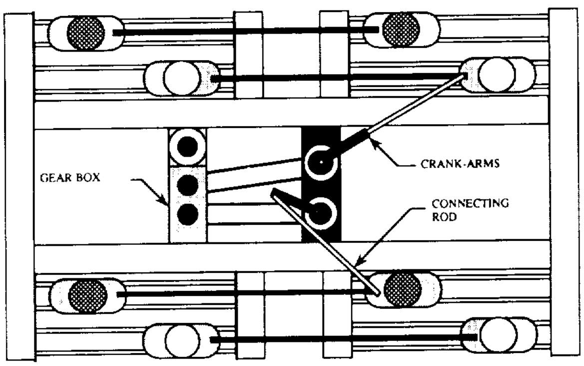


Fig. 4. Crank Arm and Connecting Rod Replacement

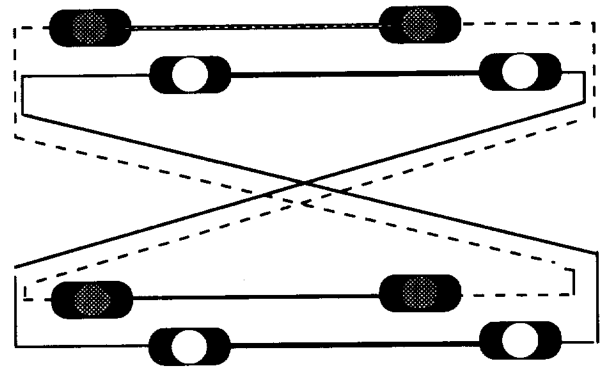


Fig. 5. Pulley Arrangement

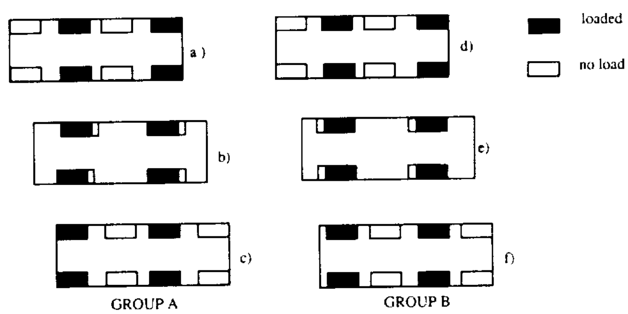


Fig. 6. Walk Routine

opposing rotation of the crank arms. Connecting rods were then attached between the crank arms and each of the forward, innermost leg support brackets. This design translates the rotational motion of the crank arm to linear motion of the legs (Fig. 4).

To achieve the goal of moving the eight legs in two groups of four, a series of connecting rods, pulleys, and cables was used. The connecting rods were attached between forward and rear leg brackets in such a way that the inner and outer sets of legs move independently, but in tandem. Cable was then routed around pulleys so that the inner group of legs on one side of the robot was connected to the outer group of legs on the other side (Fig. 5).

LEGS

Prototerp IV's leg assembly has been designed on the premise that the machine will always be resting on four of its eight legs while walking. This approach to the walking problem provides excellent stability during all phases of maneuvering. During a typical walk maneuver, the first set of the machine's four legs is supporting all the weight while the second set of four legs is transitioning to the next position. Once this position is reached, the second set of legs supports the machine while the first set then moves to the next position. Since all eight legs are coupled together, and are horizontally translated by one motor, the horizontal motion of the machine is continuous.

The transitioning set of legs remains above the supporting set of legs due to the vertical telescoping leg design. This vertical telescoping motion is adjusted by a single motor that is attached to the top of each leg. The vertical and horizontal drive mechanisms achieve the lift and translate motion that enable the machine to walk.

The following description contains the basic sequence that constitutes a step. The typical walk cycle has the machine initially supported by one set of legs. The other set is moving horizontally relative to the body at a level of about three inches above the floor. When the machine reaches the desired horizontal position, the transitioning legs are lowered and the supporting legs are then raised and begin to transition to the next desired horizontal position (Fig. 6).

Vertical translations of the legs are made possible by a telescoping design that incorporates the lower, keyed part of the leg to be driven either into or out of the upper, slotted part of the leg. A motor fixed to the top of the leg rotates a ball screw through a worm gear assembly. The ball screw, supported by bearings, drives a ball nut vertically along the screw. This ball nut is fixed to the lower portion of the leg, the inner tubing, which is keyed to fit into the slotted upper portion of the leg. The key, a delrin strip fixed to the lower part of the leg, and slot, the linear bearing of the upper leg, allow for the ball nut to remain fixed with respect to the ball screw. Thus, the leg is driven in a telescoping fashion.

The exploded diagram (Fig. 7) of the entire assembly illustrates the mechanisms that are involved in the above process. At the top of the assembly, a Pitman motor, operating at 12 V, drives the worm. An aluminum couple joins the motor shaft to the worm shaft. The other end of the worm shaft is supported by a bearing mounted on the inside of the aluminum gear box. The gear box is screwed to the top of the bearing housing. The worm drives a worm gear that is fixed to the ball screw and is supported by two bearings that are contained

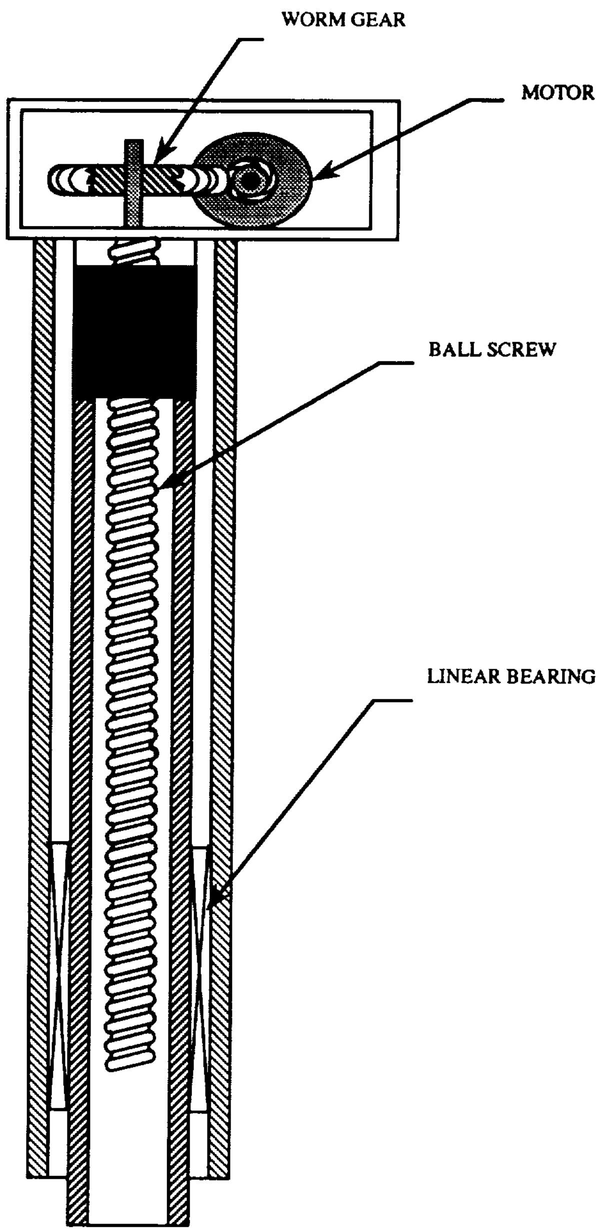


Fig. 7. Leg Assembly

in the aluminum bearing housing. This bearing housing is screwed inside the top of the outer tubing. The smaller inner tubing of the lower leg holds a linear bearing that forms a slot in which the delrin key of the lower leg slides. This key/slot of the upper and lower parts of the leg prevents rotation with respect to the upper and lower parts of the leg as the ball screw rotates. This allows the ball screw attached to the lower leg to move vertically as the ball screw rotates. The ball screw is attached to the lower part of the leg via an aluminum couple. And finally at the bottom of the lower leg is the foot, which holds the contact sensors.

CONTROL HARDWARE

The Prototerp IV walking robot control system is based on the 87C196KB 16-bit embedded microcontroller from Intel. The system is composed entirely of high-speed Complementary Metal Oxide Semiconductor (CMOS) integrated circuits. The advantage to using these circuits is that they require less current for operation and therefore conserve power. The control hardware utilizes a power source separate from that which supplies the motors. This prevents a possible voltage fluctuation from affecting the operation of the chips. A separate power source is needed because when a motor initially starts, it can cause a large power drain that in turn could cause the voltage to drop to an unacceptable level (below 3.7 V).

The control system has the capability of obtaining information on the robot's current configuration through the use of closed-loop feedback. This monitoring capability is achieved through a wide variety of sensors placed in several locations throughout the robot. The types of sensors used include encoders, short- and long-range infrared sensors, photo-interruptors, and switches (Fig. 8). Encoders are connected to each motor. They provide information pertaining to the configuration of specific components such as the height of each leg or the position of the crank arms. Infrared sensors provide information on the position of the robot relative to a specific object when the emitted infrared beam is reflected back to the sensor. Leg position is determined through the use of a photo-interruptor, which directs a light beam toward a sensor and sends a signal to the computer any time the beam is crossed. On the robot, the photo-interruptors are activated any time a leg crosses a certain position. This provides a means with which to count the number of strides taken. Finally, double position (momentary on-off) switches are located at the bottom of each leg and are used to sense when a leg makes contact with the floor.

The information from all sensors is gathered by the 87C196KB processor and is used to analyze the current status of the robot and its surroundings. Once the analysis has been completed the control system directs the machine to make any necessary adjustments.

It is the purpose of the control system to vary the robot's motors according to specific demands; to operate in either direction, at a certain speed, or to shut down. The voltage for

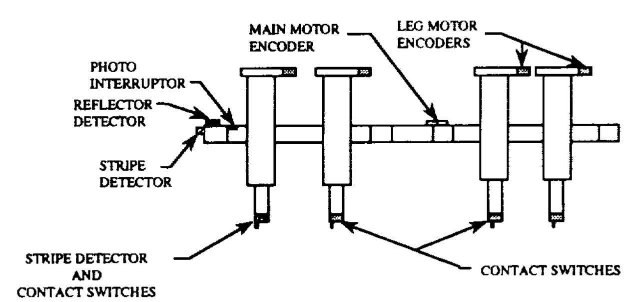
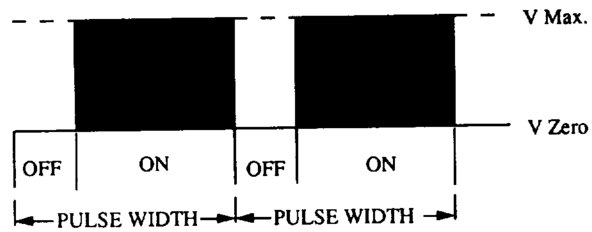


Fig. 8. Sensor Location



PROPORTIONAL VOLTAGE = [1 - (time off/time on)] x V Max

Fig. 9. PWM Waveform

the motor is controlled by a pulse-width-modulated (PWM) wave created by the control system. An illustration of a PWM wave form is shown in Fig. 9.

The PWM hardware achieves the variable speed control of a motor by adjusting the time on/time off ratio of each period of the wave form. These adjustments are repeated thousands of times per second. As the motor is incapable of reacting to these fluctuations, it interprets the signal as a percentage of the maximum voltage where the percentage is proportional to the on time of the PWM wave form.

CONTROL SOFTWARE

It is the purpose of control software to regulate all motors of the robot. These motors include (1) the main drive motor, (2) the Bigfoot motor, and (3) each of the eight leg motors.

An absolute encoder is mounted onto each motor to provide positional information about the motor. The resolution of each encoder varies from motor to motor (the resolution is 2400 counts per inch of movement of the telescoping legs, 1024 counts per revolution of the main drive motor, and 365 counts per revolution of the Bigfoot). This is an important consideration as far as control software is concerned. The different encoder resolutions imply separate yet interactive software routines for integrated operation of all motors.

There are four separate software routines designed to control the motors and coordinate their operation in performing various tasks that a planetary rover might need, such as walking, turning, or climbing.

The first-level routine is the most basic of the four. Its function is to control the operation of the motors. This is accomplished by varying the cycle time of the Pulse Width Modulators. The PWM can be varied from 0% (totally off) to 100% (full speed operation).

The second-level routine is dedicated to the interpretation of the closed-loop feedback information. This feedback information is provided through all the sensors including the infrared sensors, the motor encoders, and the leg stride photo-interruptor. Information from these sensors will be used to determine motor regulation.

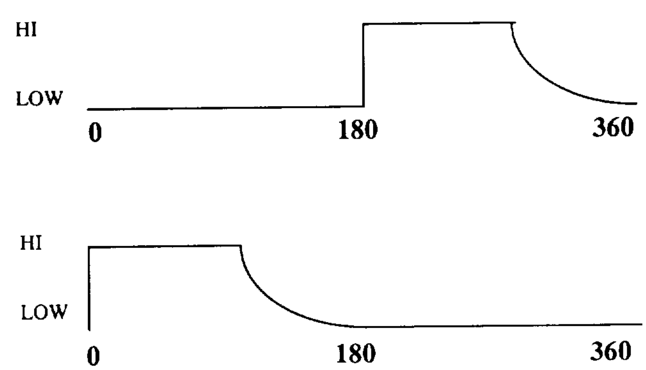
The third-level routines are dedicated to the execution of the walk routines. This software incorporates all information gathered by the sensors (second-level software) and coordinates the operation of the motors (first-level software).

The fourth and final level of software is designed to control the robot during autonomous operation. This routine has programmed into it a series of commands that will allow the robot to walk through a figure eight or walk up stairs thus demonstrating autonomous roving possibilities.

As previously stated, the robot walks on two groups of four legs. At any one time, only four legs are in contact with the ground. As each leg is mechanically linked to the drive motor, the horizontal leg location is a function of the angular position of the crank arms. The positional information of the crank arms, and thus the horizontal position of the leg assembly, is provided by the main drive motor encoder and the information regarding the vertical position of the foot is provided by the leg motor encoders. Therefore, the vertical and horizontal position of the base of the legs can be calculated at any time.

The path of the leg foot as it transitions from the nonsupporting return stroke to the supporting walk stroke was designed to follow a form based on a second-degree equation (Fig. 10). There are benefits to using a second-degree equation for the travel path of the leg feet. At some point all feet are simultaneously on the ground and by using an asymptotic approach trajectory for the foot as it finishes the return stroke, a smooth transition between stride changes is assured. Since the leg groups travel with different relative velocities most of the time, it becomes important to keep the time spent on the ground by all legs at a minimum. A second-degree decay fulfills two requirements: (1) the vertical foot positioning is at ground level for the transition; and (2) the vertical foot velocity is at a minimum when contact is made.

The control of the Bigfoot turning motor incorporates a slightly different approach to that of the legs. A proportional feedback system acts to determine the appropriate Bigfoot motor speed based on the actual and ideal robot position. By calculating the maximum angular acceleration and deceleration of the robot as it is turning, it is possible to calculate the



$y = H \times (1 - x/l)^2$ H = max height Velocity= 0 @ x = l
l = decay stride length

Fig. 10. Leg Height vs. Angular Position of Crank Arm

time required to power the Bigfoot motor to achieve the desired rotational acceleration. Then, proportional feedback is used to calculate the time when the polarity of the Bigfoot motor is to be reversed so as to decelerate the robot and stop rotation at the desired angular position.

Upon testing the machine, a backdriving problem was encountered with the telescoping legs. Because the legs can move freely in the vertical direction when no driving voltage is applied, the leg motors tend to spin backwards under the weight of the robot and the machine falls to the ground. Software control had to backdrive the legs in order to keep the vertical motion steady during the walk routines. Located in the foot of each leg is a switch that closes when it comes in contact with the floor. The status of the contact switches and the intended leg speeds developed in other routines are considered by the software routines before control voltages are sent to the motors. If the situation warrants backdriving the motors, then the lowest level routines instruct motor-control hardware circuits to send sufficient voltage as to prevent the backdriving of the motors.

CONCLUSION

The experience of designing and building Prototerp IV was unique for every person involved in the project. From the initial conception through all phases of the design, to the final details of construction, Prototerp IV has proven to be both challenging and rewarding. As an interdisciplinary experience for the students, this project has excelled. It has provided an excellent opportunity for Electrical Engineering students to learn about mechanics, and for Mechanical Engineering students to further their knowledge of electronics. The project has given these students a glimpse of the real world with all of the joys and sorrows that await them as they enter the job market as junior engineers. This experience has also shown the students the value of working harmoniously in groups; arguments don't get the job done! In addition, during the course of construction, each group was required to deal with vendors for supplies. We were often required to plead for quick delivery or bargain for donated parts, a new experience for many of the students. In short, every member of the Prototerp IV team was required to learn and grow along with the robot.

ACKNOWLEDGMENTS

Support for the University of Maryland Walking Machine project was given through a grant from NASA/USRA Advanced Design Program. This support is gratefully acknowledged. The students of EMNE 480 would also like to thank Bob Anders, of the University of Maryland Engineering Machine Shop, and Bob Lincoln, of the University of Maryland Electronics Laboratory, for their technical advice and unending support of our efforts. Finally, we would like to thank Mark Uebel, our teaching assistant during this project, for without his direction, concern, and all those sleepless nights toward the end, Prototerp IV would not be a reality.

REFERENCES

1. Shigley, Joseph Edward. *Mechanical Engineering Design*. McGraw-Hill Book Company, New York. 1989.
2. Willems, Nicholas, John T. Easley and Stanley T. Rolfe. *Strength of Materials*. McGraw-Hill Book Company, New York. 1981.